ESC European Society of Cardiology

European Heart Journal: Acute Cardiovascular Care (2025) **00**, 1–3
https://doi.org/10.1093/ehjacc/zuaf075

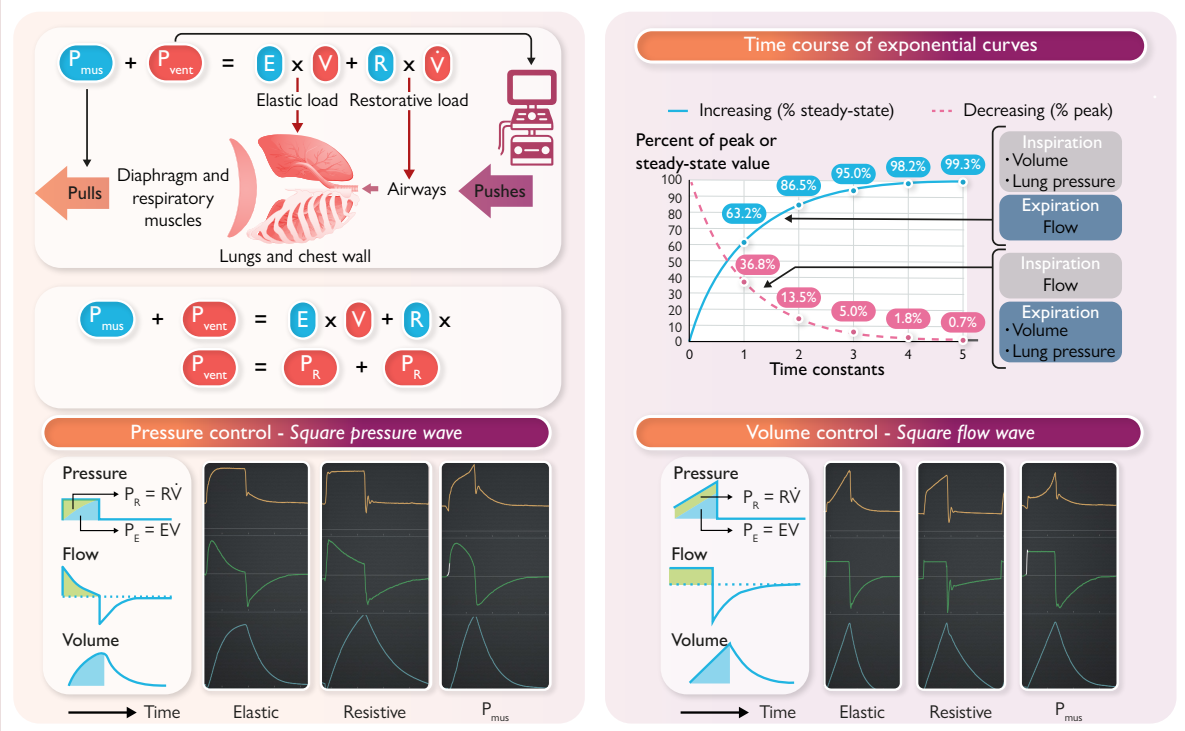
EDITORIAL

The equation of motion: a brief guide to ventilator adjustment

Eduardo Mireles-Cabodevila [1]* and Robert L. Chatburn [2]

[1]Department of Pulmonary and Critical Care Medicine, Integrated Hospital Care Institute, Cleveland Clinic, 9500 Euclid Ave, Cleveland, OH 44195, USA; and [2]Respiratory Therapy, Cleveland Clinic, Cleveland, OH, USA

Graphical Abstract



Downloaded from https://academic.oup.com/ehjacc/advance-article/doi/10.1093/ehjacc/zuaf075/8195106 by Universidade do Estado do Rio de Janeiro user on 11 July 2025

The views and opinions expressed in this article are those of the authors; they do not necessarily reflect the views of the Editors.

* Corresponding author. Tel: 216-445-2523, Email: mirelee@ccf.org

© The Author(s) 2025. Published by Oxford University Press on behalf of the European Society of Cardiology. All rights reserved. For commercial re-use, please contact reprints@oup.com for reprints and translation rights for reprints. All other permissions can be obtained through our RightsLink service via the Permissions link on the article page on our site—for further information please contact journals.permissions@oup.com.

SHOUT
SHARE
IT

This visual abstract illustrates the equation of motion (EoM) for the respiratory system and its clinical manifestations when pressure or volume are controlled. The left upper diagram shows the EoM: airway pressure above set PEEP (P_{vent}) and patient-generated pressure (P_{mus}) combine to overcome both elastic ($E \times V$) and resistive ($R \times \dot{V}$) loads during mechanical ventilation. On the lower left, pressure control ventilation is demonstrated with a square pressure waveform, and waveform patterns are shown for isolated increases in elastic load, resistive load, and inspiratory effort (P_{mus}). The flow and volume responses under each condition highlight deviations from the expected exponential decay, governed by the time constant ($\tau = R \times C$), as emphasized in the upper right graph. On the lower right, volume control ventilation is depicted with a square flow waveform. Again, isolated alterations in load or effort produce distinct changes in the pressure waveform. These visual abstract reinforce the application of the EoM at the bedside and provide a framework for interpreting pressure, flow, and volume waveforms.

Ventilator waveforms provide real-time insight into the mechanical behaviour of the respiratory system. They are direct representations of the equation of motion (EoM), which forms the theoretical basis of mechanical ventilation by defining the pressure required to move gas into the lungs as the sum of resistive and elastic loads.[1] This relationship can be expressed in its general form as a first-order linear differential equation:

$$P_{aw}(t) + P_{mus}(t) = E \cdot V(t) + R \cdot \dot{V}(t) + PEEP_{set} + PEEP_{auto}, \quad (1)$$

where:

$P_{aw}(t)$ = the airway pressure (relative to atmospheric pressure)
$P_{mus}(t)$ = the pressure generated by the patient's inspiratory muscles
R = resistance (cm H_2O/L/s)
$\dot{V}(t)$ = flow (L/s)
E = elastance (cm H_2O/L)
$V(t)$ = volume above end-expiratory volume
$PEEP_{set}$ = set positive end-expiratory pressure
$PEEP_{auto}$ = pressure due to gas trapping
t = time.

This equation can be simplified for bedside use by assuming $PEEP_{auto} = 0$ and expressing pressures relative to $PEEP_{set}$. The simplified form becomes:

$$P_{vent} + P_{mus} = E \cdot V + R \cdot \dot{V}. \quad (2)$$

Here, P_{vent} is the pressure generated by the ventilator above $PEEP_{set}$. The total pressure applied to the respiratory system ($P_{vent} + P_{mus}$) must match the pressure required to overcome resistive and elastic loads. This form enables rapid assessment of the interaction between ventilator support and patient effort.

Mechanical ventilators only control one side of the EoM at a time.[2] Volume control (VC) controls flow and volume (right-hand side), such that $P_{aw}(t)$ becomes the dependent variable, reflecting changes in resistance and elastance. Pressure control (PC) modes control $P_{aw}(t)$, making flow and volume a manifestation of the respiratory system's mechanical properties.

This unidirectional control concept is critical: it defines which variables are 'fixed' inputs and which must be interpreted as outputs of system behaviour. The inability of ventilators to simultaneously control both sides of the EoM ensures that alterations in respiratory system mechanics manifest waveform distortions, which can be diagnostically useful.

During PC ventilation, $P_{aw}(t)$ is held constant throughout inspiration. Assuming passive conditions ($P_{mus} = 0$), Equation 1 can be used to derive expressions for $V(t)$ and $\dot{V}(t)$. These are exponential functions whose rate of change is governed by the time constant (τ) of the respiratory system.[3]

$$\tau = R \times C. \quad (3)$$

The time constant, τ, represents the time required for an exponential function for $V(t)$ or $\dot{V}(t)$ to change by 63% (either from zero to equilibrium value for V or from the peak value to zero for $\dot{V}$ during inspiration). For expiration, 3τ are generally accepted as sufficient to achieve 95% emptying.

Because τ governs the temporal behaviour of the respiratory system in both inspiration and expiration under passive conditions, we can use it to interpret flow waveforms; A short τ (low compliance, C, or high E) produces a rapid return of flow to zero; a long τ (usually due to high R, or less commonly high C) results in a slower return to zero. This is only visible in the absence of P_{mus}. The clinical application is as follows: for an intubated adult with normal lungs, 3τ is $\sim 1.8 \pm 0.2$ s.[4] As a heuristic, flow returning to baseline in <1.6 s suggests an elastic load, while >2.0 s suggests a dominant resistive load.

In VC modes, the analysis is algebraic. A square (constant) flow waveform implies that the initial inspiratory pressure rise is due to resistive load (since volume = 0 at initiation), and later pressure rise (slope) is due to elastic load (as volume increases linearly). A plateau pressure measured during an inspiratory hold reflects the elastic load alone, since flow = 0 and the resistive term vanishes. This provides a discrete method for visually quantifying E and R in the absence of P_{mus}.[5]

The presence of P_{mus} alters waveform morphology and must be considered when assessing waveforms. During the inspiratory time with VC, where flow and volume are present, inspiratory (positive P_{mus}) lowers P_{vent}, while expiratory effort (negative P_{mus}) raises it. During the inspiratory time with PC, where pressure is preset, inspiratory effort increases flow and volume, and expiratory effort decreases them. In all modes, expiratory efforts may appear as deviations from the expected passive exponential flow decay. Failure to recognize P_{mus} can mislead interpretation of system load, though careful observation may recognize brief passive periods suitable for assessing mechanics.

The EoM has been used for automatic waveform interpretation. There are several examples. In VC, deviations in pressure slope are quantified as a stress index, used to infer intratidal recruitment or overdistention.[6] In PC, the flow index evaluates deviation from expected exponential decay to infer the presence and timing of P_{mus}.[7] These techniques facilitate interpretation of waveform data by referencing the expected behaviour according to the EoM. In proportional assist ventilation, R and E are continuously estimated and the ventilator delivers inspiratory pressure proportional to the calculated P_{mus}. Here, the EoM is the basis for a real-time control algorithm.[8]

In sum, the EoM provides the theoretical framework upon which mechanical ventilation is built. It highlights the boundaries of ventilator control, the diagnostic utility of waveform, and the logic behind technological development. This brief summary on a complex topic should help as a starting point to mastery of the EoM and its application at bedside.

Downloaded from https://academic.oup.com/ehjacc/advance-article/doi/10.1093/ehjacc/zuaf075/8195106 by Universidade do Estado do Rio de Janeiro user on 11 July 2025

Funding

No external funding was received for this project.

Conflict of interest: E.M.C. and R.L.C. are co-creators of the SEVA program. R.L.C. is consultant for University of Cincinnati, IngMar, Promedic, Ventis.

References

1. Chatburn RL, Kacmarek R. Chapter 47—Physiology of ventilatory support. In: *Egan's Fundamentals of Respiratory Care*. 13th ed. St.Louis Missouri: Elsevier; 2025. p. 1008–1048.
2. Chatburn RL, El-Khatib M, Mireles-Cabodevila E. A taxonomy for mechanical ventilation: 10 fundamental maxims. *Respir Care* 2014;**59**:1747–1763.
3. McIlroy MB, Tierney DF, Nadel JA. A new method for measurement of compliance and resistance of lungs and thorax. *J Appl Physiol* 1963;**18**:424–427.
4. Arnal J-M, Garnero A, Saoli M, Chatburn RL. Parameters for simulation of adult subjects during mechanical ventilation. *Respir Care* 2018;**63**:158–168.
5. Mireles-Cabodevila E, Siuba MT, Chatburn RL. A taxonomy for patient-ventilator interactions and a method to read ventilator waveforms. *Respir Care* 2022;**67**:129–148.
6. Grasso S, Terragni P, Mascia L, Fanelli V, Quintel M, Herrmann P, *et al.* Airway pressure-time curve profile (stress index) detects tidal recruitment/hyperinflation in experimental acute lung injury. *Crit Care Med* 2004;**32**:1018–1027.
7. Albani F, Fusina F, Ciabatti G, Pisani L, Lippolis V, Franceschetti ME, *et al.* Flow Index accurately identifies breaths with low or high inspiratory effort during pressure support ventilation. *Crit Care* 2021;**25**:427.
8. Chatburn RL, Mireles-Cabodevila E. Closed-loop control of mechanical ventilation: description and classification of targeting schemes. *Respir Care* 2011;**56**:85–102.

Downloaded from https://academic.oup.com/ehjacc/advance-article/doi/10.1093/ehjacc/zuaf075/8195106 by Universidade do Estado do Rio de Janeiro user on 11 July 2025